CERN-TH.7167/94

UNIFICATION OF FUNDAMENTAL INTERACTIONS IN SUPERSYMMETRY [1]

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Abstract

A review is given of recent developments on the implications of supergravity grand unification with SU(5)-type proton decay under the condition $M_{H_3}/m_G < 10$ (where M_{H_3} is the Higgs triplet mass) and the naturalness condition that the universal scalar mass m_0 and the gluino mass are < 1 TeV. It is shown that the maximum achievable lifetime limits on proton lifetime at Super Kamiokande and ICARUS will exhaust the full parameter space of the model under the constraint $m_{\tilde{W}_1} > 100$ GeV. Thus the model predicts the observation of either a light chargino with mass $\lesssim 100$ GeV, or the observation of a $\bar{\nu}K^+$ mode at Super Kamiokande and ICARUS within the above naturalness constraints. Analysis of the $b \to s\gamma$ branching ratio within this model is also discussed. It is shown that there is a significant region of the parameter space where the branching ratio predicted by the model lies within the current experimental bounds. It is pointed out that improved measurements of $B(b \to s\gamma)$ will significantly delineate the parameter space of the model and allow for a more stringent determination of their allowed ranges.

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[1] Invited Talk at the Conference on "Unified Symmetry in the Small and in the Large", at Coral Gables, Florida, Jan 27–30, 1994.

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CERN-TH.7167/94
February 1994

I. Introduction

One of the important developments over the past three years has been the demonstration that the high precision LEP data [1], when extrapolated to high energy using renormalization group equations, leads to unification of the $\mathrm{SU(3)_C} \times \mathrm{SU(2)_L} \times \mathrm{U(1)}$ coupling constants α_3, α_2 and α_1 (where $\alpha_1 = \frac{5}{3}\alpha_Y$ and α_Y is the hypercharge coupling constant) within the standard supersymmetric SU(5) theory [2]. Supergravity grand unification provides an attractive mechanism for the unification of the electroweak and the strong interactions as well as a framework where supersymmetry can be broken in a consistent fashion [3],[4]. Thus the spontaneous breaking of supersymmetry in unified supergravity models leads to an enormous reduction [3], [5]–[7] in the number of arbitrary SUSY-breaking parameters that one encounters in globally supersymmetric theories [8].

We begin by reviewing briefly the ideas of supergravity grand unification. Our starting assumption is the existence of an $N = 1$ supergravity unified theory below the Planck scale $M_{Pl} = 2.4 \times 10^{18}$ GeV. This unified theory can be completely specified in terms of three functions. These are: (1) superpotential $W(z_a)$, which is a holomorphic function of the chiral fields, (2) a Kähler potential $K(z_a, z_a^*)$, which depends both on the chiral fields and on their complex conjugates, and (3) a gauge kinetic energy function $f_{\alpha\beta}$, which also is a function of the fields and their complex conjugates. One obtains a gaugino mass from supergravity couplings, which is of the form

$$\frac{1}{4}\bar{e}^{\frac{G}{2}}(G^{-1})^a_b\ G,^{\ a}\ \ f^*_{\alpha\beta,b}\bar{\lambda}^\alpha\lambda^\beta \tag{1.1}$$

where $G = -\ln[\kappa^6 WW^*] - \kappa^2 K$, and $\kappa = (M_{Pl})^{-1}$. We shall make the standard assumptions that appear in the formulation of superunified models. First we shall assume that supersymmetry is broken by a gauge singlet field in the hidden sector [3],[5]. Next, we shall assume that the Kähler potential is generation-blind at the GUT scale so that FCNC will be suppressed at low energies, and that the superpotential is restricted to renormalizable interactions (although an understanding of the full quark and lepton mass hierarchy may require inclusion of higher dimensioned operators). With the above assumptions, one can generate a low energy effective theory below the GUT scale, where the gauge group is $\mathrm{SU(3)_C}\times \mathrm{SU(2)_L}\times \mathrm{U(1)_Y}$ and the superheavy sector is integrated out. The effective potential of this theory is given by $V_{eff} = V_{SS}+V_{SB}$ where V_{SS} is the supersymmetry-invariant part and V_{SB} is the symmetry-breaking part. In supergravity a very simple form emerges for V_{SB}:

$$V_{SB} = \sum_i m_0^2 z_i z_i^+ + \left(A_0 W^{(3)} + B_0 W^{(2)} + M_{H_3}^{-1} W^{(4)}\right)\ , \tag{1.2}$$

where $W^{(2)}$ is the quadratic, $W^{(3)}$ is the cubic and $W^{(4)}$ the quartic part of the effective superpotential below the GUT scale. After SUSY breaking, Eq. (1.1) gives a gaugino mass term of the form $m_{\frac{1}{2}}\bar{\lambda}^\alpha\lambda^\alpha$, so that together with Eq. (1.2) one has a total of four soft SUSY-breaking parameters

$$m_0,\ m_{\frac{1}{2}},\ A_0,\ B_0\ . \tag{1.3}$$

A phenomenologically interesting GUT group in general could be an SU(5), SO(10), E(6), etc. We shall assume that the specific model we are considering is or contains an SU(5). For the

spectrum, we shall assume three generations of quarks and leptons in $5+\overline{10}$ representations, and two plets of Higgs (H_1, H_2) in $(5,\overline{5})$ representations. At low energy, the effective superpotential will then have a quadratic term of the form $W^{(2)} = \mu_0 H_1 H_2$, where H_1, H_2 now refer to the Higgs doublets in the respective multiplets.

The outline of the rest of the paper is as follows: in Section 2, we discuss the analysis using radiative electroweak symmetry breaking under a number of constraints which are physically desirable. In Section 3, we discuss the question whether Super Kamiokande and ICARUS can test SUGRA GUTs. In Section 4, we discuss $b \to s\gamma$ decay in SU(5) SUGRA GUTs. Conclusions are given in Section 5.

II. Analysis using radiative electroweak symmetry breaking

As is well known an attractive feature of supergravity grand unification is that it can generate its own electroweak symmetry breaking via renormalization group effects [9]. Under the assumption of charge and colour conservation, the potential that governs symmetry breaking in supergravity models is given by $V = V_0 + \Delta V_1$, where V_0 is the renormalization group improved semi-classical tree potential

$$\begin{aligned} V_0(Q) &= m_1^2(t)|H_1|^2 + m_2^2(t)|H_2|^2 - m_3^2(t)(H_1H_2 + \text{h.c.}) \\ &+ \frac{1}{2}(g_2^2 + g_Y^2)(|H_1|^2 - |H_2|^2)^2 \end{aligned} \tag{2.1}$$

and ΔV_1 gives the one-loop correction [10]$-$[12]

$$\Delta V_1 = \frac{1}{64\pi^2}\sum_i (-1)^{2j_i+1} n_i \left[M_i^4\left(\log\frac{M_i^2}{Q^2} - \frac{3}{2}\right)\right] . \tag{2.2}$$

The analysis of electroweak symmetry breaking is carried out by what has now become a standard procedure. One evolves the renormalization group equations on gauge and Yukawa couplings and on soft SUSY-breaking terms. In addition to the charge and colour conservation, one imposes CDF and LEP lower bounds and naturalness upper limit of 1 TeV on m_0 and m_{gluino}.

Additionally, in supergravity GUTs one imposes the proton lifetime lower limits from Kamiokande/IMB experiments. The radiative breaking analysis [13] determines the parameter μ_0 by fixing M_Z, and the parameter B_0 can be traded in favour of $\tan\beta$. Thus the theory may be described by the four parameters

$$m_0\ ,\quad m_{\frac{1}{2}}\ ,\quad A_0\ ,\quad \tan\beta\ . \tag{2.3}$$

There are 32 supersymmetric particles in the theory, whose masses can be computed in terms of the four parameters of Eq. (2.3). Thus there are 28 predictions relating the SUSY masses in supergravity unification [13]$-$[24].

Some of the main results of the analysis described above are now discussed:

(1) Scaling laws [13]−[15]: For a large part of the parameter space one finds $\mu \gg M_Z$, and scaling laws emerge. Specifically for the neutralino and chargino masses one finds the relation

$$2m_{\tilde{Z}_1} \simeq m_{\tilde{W}_1} \simeq m_{\tilde{Z}_2} \tag{2.4a}$$

$$m_{\tilde{Z}_3} \simeq m_{\tilde{Z}_4} \simeq m_{\tilde{W}_2} \simeq |\mu| \tag{2.4b}$$

$$m_{\tilde{W}_1} \simeq \frac{1}{4} m_{\tilde{g}}(\mu > 0), \quad m_{\tilde{W}_1} \simeq \frac{1}{3} m_{\tilde{g}}(\mu < 0) \ . \tag{2.4c}$$

Similarly the four Higgs bosons, except the lightest Higgs (h^0), are seen to have essentially degenerate masses:

$$m_{H^+} \simeq m_{H^0} \simeq m_A \ . \tag{2.5}$$

(2) Limits on the light Higgs and the top [13],[14]: The analysis gives upper limits that are

$$m_{h^0} \lesssim 110{-}120 \text{ GeV} \tag{2.6a}$$

$$m_t \lesssim 180{-}190 \text{ GeV} \ . \tag{2.6b}$$

(3) Other spectra: Radiative electroweak symmetry breaking and proton stability coonstrain other SUSY mass spectra as well. The proton stability constraint can be easily understood in a qualitative fashion in the limit when m_0 is large. This limit gives, for the dressing loop function B [see Eq. (3.2)], the result

$$B \simeq -2\left(\frac{\alpha_2}{\alpha_3}\sin 2\beta\right)\left(m_{\tilde{g}}/m_{\tilde{q}}^2\right) \tag{2.7}$$

and the approximate relation $m_{\tilde{q}}^2 = m_0^2 + 0.65 m_{\tilde{q}}^2$. Thus a small gluino mass, a large squark mass and a small $\tan\beta$ are favoured by proton stability. Typically this implies that the first two generations fo squarks will be essentially degenerate in mass and heavier than the gluino. Similarly, masses of the three generations of sleptons will be essentially degenerate and large, but lighter than the first two generations of squarks. Masses of the third generation of squarks is more complicated, because a heavy top mass can lead to a very small mass for the lighter of the two stop masses. In fact the condition that the stop masses not turn tachyonic acts as a constraint on the parameter space of the model. Proton stability constraints also give a lower limit on the mass of the A-Higgs boson, which is significantly larger than what is obtained from electroweak symmetry breaking alone. In this context we recall that there exists a hole in the parameter space of the MSSM which extends roughly from 100 to 200 GeV (with $\tan\beta$ in the range $5 \lesssim \tan\beta \lesssim 20$) which cannot be explored by LEP2 and LHC experiments [25]. The constraints of radiative electroweak symmetry breaking with proton stability already give a lower bound on the A-Higgs mass that closes this gap.

III. Can the SUGRA GUT be tested at Super Kamiokande and ICARUS?

There already exist stringent limits on the proton lifetime, and these limits are expected to improve significantly in the new generation of proton stability experiments, i.e. Super Kamiokande and ICARUS. One may ask if the expected increase in the sensitivity of these proton decay experiments will be able to test in a conclusive fashion at least a class of SUGRA GUT models. To quantify the discussion, we shall assume that the GUT group G we are dealing with is or contains an SU(5). We assume further that at the GUT scale, the GUT group G breaks into the Standard Model gauge group $\mathrm{SU(3)_C} \times \mathrm{SU(2)_L} \times \mathrm{U(1)_Y}$. We also assume the existence of just two doublets of Higgs, which are embedded in $5+\overline{5}$ of SU(5). Finally, we assume that there are no discrete symmetries in the model which forbid proton decay. We shall focus here on the dominant decay mode of $p \to \bar{\nu}K^+$. One can easily show that there is a model-independent amplitude for the above mode which goes via the exchange of the colour triplet Higgsino field $\tilde{H}_3$, and one may write the decay width as

$$\Gamma(p \to \bar{\nu}K^+) = \mathrm{Const}\left(\frac{\beta_p}{m_{H_3}}\right)^2 |B|^2 \ . \tag{3.1}$$

In Eq. (3.1), the Const is a product of phase-space and chiral Lagrangian factors [26], β_p is the three-quark matrix element of the proton, whose value is known from lattice gauge theory, M_{H_3} is the Higgsino triplet mass and B is the dressing loop function defined in Refs. [13]–[14]. Using the current experimental lower limit on this mode, which is [27] $\tau(p \to \bar{\nu}K^+) > 1.0 \times 10^{32}$ yr, one finds on using Eq. (3.1) an upper limit of

$$B \lesssim 100(M_{H_3}/M_G)\ \mathrm{GeV}^{-1} \ , \tag{3.2}$$

where we expect $M_{H_3}/M_G \lesssim 10$. In the future, Super Kamiokande and ICARUS are expected to reach lower limits of

$$\text{Super Kamiokande [28] } \tau(p \to \bar{\nu}K^+) > 2 \times 10^{33}\mathrm{yr} \tag{3.3a}$$

$$\text{ICARUS [29] } \tau(p \to \bar{\nu}K^+) > 5 \times 10^{33}\mathrm{yr} \tag{3.3b}$$

In view of the increased sensitivity expected in these experiments, one may ask if Eq. (3.3) will exhaust the full parameter space of the SU(5)-type SUGRA GUT. A detailed analysis of this question shows [30] that Eq. (3.3) would not itself be able to exhaust the full parameter space of the SU(5)-type GUT. However, it was found that Super Kamiokande and ICARUS experiments, along with maximum achievable superparticle mass limits at LEP2 and at the Tevatron can exhaust the full parameter space [30]. Specifically one finds the following results [30]:

(a) If $\tau(p \to \bar{\nu}K^+) > 1.5 \times 10^{33}$yr, then either $m_{h^0} \lesssim 95$ GeV or $m_{\tilde{W}_1} < 100$ GeV. Thus either h^0 or $\tilde{W}_1$ (and possibly both) will be observable at LEP2, provided LEP2 can reach its optimum energy and luminosity.

(b) Either the $\bar{\nu}K^+$ mode should be seen at the Super Kamiokande and ICARUS experiments, or the $\tilde{W}_1$ should be seen at LEP2.

The result of case (b) above is exhibited in Fig. 1, where the maximum value of $\tau(p \to \bar{\nu}K)$ is given when $m_{\tilde{W}_1} > 100$ GeV, for the case $\mu > 0$ and $m_t = 150$ GeV. The maximum lifetime at a given m_0 is obtained by exhausting the allowed domain in the rest of the parameter space, i.e. $m_{\tilde{g}}, A_t, \tan\beta$. Figure 1 shows that with $M_{H_3}/M_G < 10$, ICARUS will exhaust the entire parameter space of the SU(5)-type SUGRA GUT under the restriction that $m_{\tilde{W}_1} > 100$ GeV. Thus the conclusion of (b) above follows. The above analysis shows that the SU(5)-type SUGRA GUT can be tested by using a combination of accelerator and non-accelerator experiments.

IV. $b \to s\gamma$ DECAY IN SUGRA GUT

Recently CLEO [31] has obtained a new upper bound on the inclusive process $b \to s\gamma$ with a value $BR(b \to s\gamma) < 5.4 \times 10^{-4}$ [at 95% CL]. They also observe a non-vanishing result for the exclusive mode $B \to K^*\gamma$ with a branching ratio of 5×10^{-5}. Assuming that the $K^*\gamma$ contributes $\approx 15\%$ to the inclusive process, as is indicated by lattice gauge calculations [32], one obtains also a lower limit $BR(b \to s\gamma) > 1.5 \times 10^{-5}$. The branching ratio measurements on $b \to s\gamma$ are expected to improve in the future, both with analysis of additional data at CLEO and from data that would emerge from B-factories, where one expects luminosities that would be an order of magnitude larger than at current machines. The Standard Model result would then be put to a severe test, and any deviation from it would signal the onset of new physics beyond the SM.

In the SM, $b \to s\gamma$ proceeds via a penguin, which involves exchange of a W boson and gives $BR(b \to s\gamma) \simeq 3.5 \times 10^{-4}$. This result is ambiguous up to few per cent since the BR is a sensitive function of the inputs such as quark masses and α_3, which currently have some inherent experimental errors. Additionally, the current analyses of the BR are done only to leading order QCD corrections, and there may be important beyond the leading-order corrections which have not yet been fully computed [33]. There are additional penguins in supergravity which contribute to this branching ratio. These involve the exchange of charged Higgses, charginos, gluinos and neutralinos [34]–[36]. We summarize here results of a recent analysis of these contributions within the framework of electroweak symmetry [37],[38] and SUGRA GUT constraints including the constraint of proton stability [37].

In the SUGRA GUT analysis here we compute the contributions from W, charged Higgses and charginos and neglect small contributions from the neutralino and gluino exchanges. To leading order QCD corrections, one has [39],[34],[35]

$$\frac{BR(b \to s\gamma)}{BR(b \to ce\nu)} = \frac{6\alpha}{\pi} \frac{\left[\eta^{\frac{16}{32}} A_\gamma + \frac{8}{3}\left(\eta^{\frac{14}{23}} - \eta^{\frac{16}{32}} A_g\right) + C\right]^2}{P\left(\frac{m_c}{m_b}\right)\left[1 - \frac{2}{3\pi}\alpha_s(m_b)\left(\frac{m_c}{m_b}\right)\right]} \tag{4.1}$$

where $\eta = \alpha_s(m_Z)/\alpha_s(m_b)$, $f(m_c/m_b) = 0.241$, C is an operator mixing coefficient and P is a phase space factor. For C we use the recent analysis of Ref. [40].

For the case of the SUGRA SU(5) GUT one finds [37] that there is a significant region of the parameter space where the branching ratio $BR(b \to s\gamma)$ lies within the current experimental bound.

Results for the case $\mu > 0$ and $m_t = 150$ GeV are exhibited in Fig. 2. The vertical line at $B = 1000\ \mathrm{GeV}^{-1}$ gives the current value of the Kamiokande experimental bound with m_{H_3}/M_G $= 10$. The region to the right of this vertical line is thus forbidden by p-stability while the region to the left is allowed. We see that the branching ratio can be either larger and smaller than the SM value in the allowed domain, with significant deviations from the SM value occurring in both directions. The analysis of the $\mu < 0$ case, although quantitatively different, is similar to the $\mu > 0$ case. Again one finds here a significant region of the parameter space where the model gives a $b \to s\gamma$ branching ratio within the current experimental bounds.

The $b \to s\gamma$ branching ratio is also a sensitive function of the hidden sector parameter A_t, and of $\tan\beta$. In SUGRA SU(5) GUT $\tan\beta$ is limited by p-stability in such a way that $\tan\beta < 7 - 8$. If the constraint of p-stability is eliminated, $\tan\beta$ becomes unrestricted and much larger variations in the $b \to s\gamma$ branching ratio can be generated [38].

b–τ unification: Recent analyses on b–τ masses within SUSY SU(5)-type models point to rather stringent constraints on $\tan\beta$. Specifically it is found that the constraint of the equality of the b–τ Yukawa couplings at the GUT scale implies that the top mass lies close to its fixed point value [41]. The analyses reveal two branches in $\tan\beta$ for fixed m_t. For the range of the top mass in the LEP favoured region of 130–170 GeV, $\tan\beta$ is found to be either small (< 2) or very large (> 50). These constraints on $\tan\beta$ are rather severe, and it is reasonable to ask how rigid they are. Before a fixed conclusion can be drawn, it is necessary to carry out a re-evaluation of the inputs used in the analyses. These include the b and τ masses, α_3, as well as specific assumptions made in the renormalization group analyses, such as the treatment of the low energy and GUT thresholds. Aside from the above there is the philosophical issue of whether it is reasonable to impose a strict b–τ unification since s–μ and d–e unification are not nearly as good. This latter feature points to the possibility of higher-dimensional operators or Planck slop terms at the GUT scale. The existence of such operators appears reasonable in view of the fact that we are dealing with an effective theory, even at the GUT scale, and there may be quantum gravity corrections induced at this scale due to new physics at the Planck scale. Inclusion of such Planck slop terms via higher-dimensional operators indicates a loosening of the stringent constraints discussed above [42].

V. CONCLUSIONS

Supergravity SU(5) GUT is a leading contender for the unification of electroweak and strong interactions. The model is presently consistent with all known experiment, and makes predictions that are accessible at current accelerator and non-accelerator experiments, and at machines that are expected to go on line in the near future. Specifically in this review, it was shown that although Super Kamiokande and ICARUS by themselves cannot exhaust the full parameter

space of SU(5)-type supergravity GUTs, they can do so when combined with the maximum achievable superparticle mass limits at LEP2 and the Tevatron. An analysis of the $b \to s\gamma$ decay in the SU(5) supergravity GUT was also given. It is found that there is a significant region of the parameter space where the $BR(b \to s\gamma)$ predicted by the theory lies within the current experimental bounds. It is pointed out that improved experimental limits may be able to put more stringent constraints on the parameters of supergravity GUTs.

ACKNOWLEDGEMENTS

This research was supported in part by NSF Grant Nos. PHY-19306906 and PHY-916593.

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Fig. 1: Maximum value of $\tau(p \to \bar{\nu} K^+)$ when $m_{\tilde{W}_1} > 100$ GeV as a function of m_0, for the case $m_t = 150$ GeV and $\mu > 0$ from Ref. [30]. The solid, dashed and dot-dashed lines correspond to $m_{H_3}/M_G = 3, 6$ and 10. The lowest horizontal line is the current experimental limit. For the two horizontal lines above, the lower and higher lines are the upper bound for Super Kamiokande and ICARUS, i.e. the experiments are sensitive to lifetimes below these lines.

Fig. 2: $BR(b \to s\gamma)$ in the SU(5) supergravity GUT for $\mu > 0$ and $m_t = 150$ GeV.